CP violation at the finite temperature and baryon asymmetry in the 2HDMS

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2025.3.28-4.1

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Outline：

- Brief overview of EWBG
- Introduction to the model
- Theoretical and experimental constraints
- Results and discussions
- Conclusions

Electroweak Baryogenesis (EWBG)

The observed baryon asymmetry of the universe (BAU) from the Big Bang Nucleosynthesis:

$$Y_B \equiv \rho_B/s = (8.2 - 9.2) \times 10^{-11}$$

P. A. Zyla et al. [Particle Data Group], Review of Particle Physics, PTEP 2020, 083C01 (2020).

Generating such an asymmetry dynamically need satisfy the well-known Sakharov conditions:

(1) baryon number violation, (2) C and CP violation, (3) departure from thermal equilibrium

EWBG:

Sphaleron process

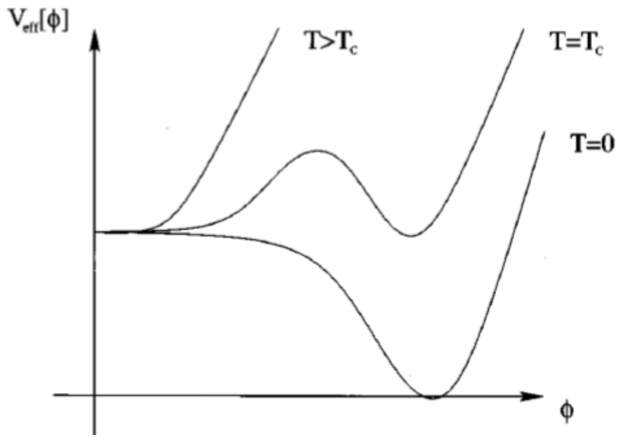
Sufficient CP-violation sources need to be added

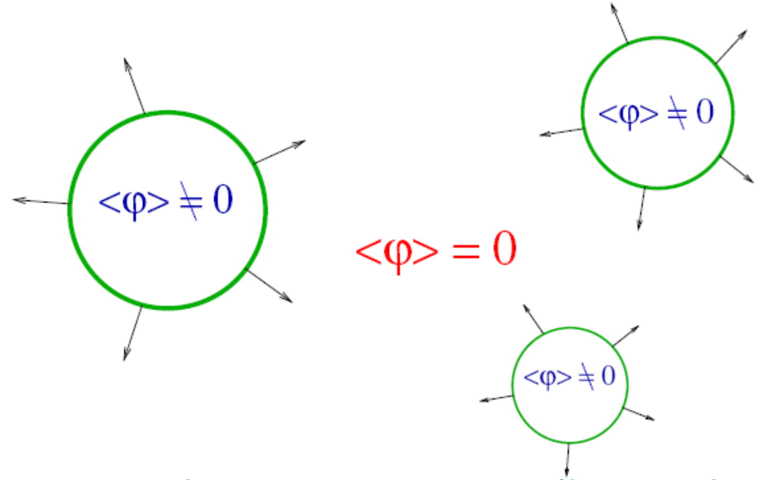
A strongly first-order electroweak phase transition

A. D. Sakharov, Violation of CP Invariance, C asymmetry, and baryon asymmetry of the universe, Pisma Zh. Eksp. Teor. Fiz. 5, 32-35 (1967).

V. A. Kuzmin, V.A. Rubakov, M. E. Shaposhnikov, Phys. Lett. B 155, 36 (1985).

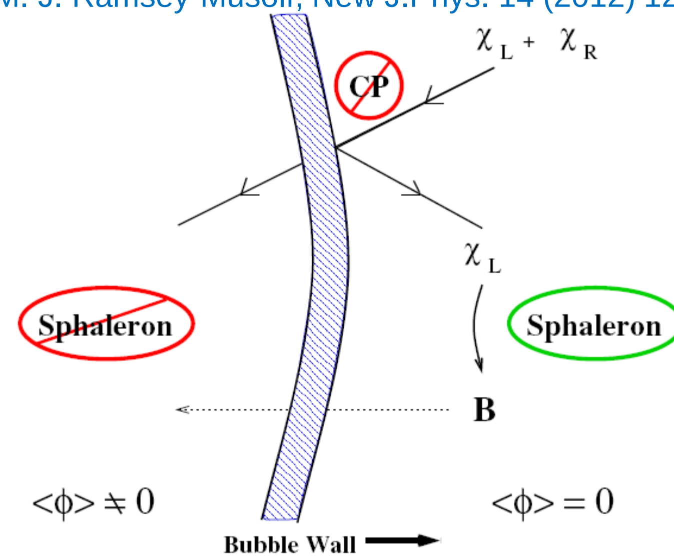
V. A. Rubakov, M. E. Shaposhnikov, Usp. Fiz. Nauk 166, 493 (1996); Phys. Usp. 39, 461 (1996).





D. E. Morrissey, M. J. Ramsey-Musolf, New J.Phys. 14 (2012) 125003

first-order electroweak PT



The BAU is genertated during the first-order electroweak PT:

The CP violation and EDM:

$$d_f \sim \sin\phi \left(\frac{m_f}{\mathrm{MeV}}\right)\left(\frac{1\,\mathrm{TeV}}{M}\right)^2 \times 10^{-26}\, e\,\mathrm{cm}.$$

The bound on electron EDM

$$|d_e| < 10.5 \times 10^{-28}\ e\,\mathrm{cm}$$

ACME collaboration, J. Baron et al., Science 343, 269 (2014)

Solutions to alleviate electron EDM constraints

(1) In the SM extension with a real singlet scalar field, the real singlet scalar field has no vacuum expectation value at zero temperature.

$$V(H,s) = \mu_h^2 H^\dagger H + \lambda_h \left(H^\dagger H\right)^2 + \frac{\lambda_{hs}}{2}\left(H^\dagger H\right)s^2 + \frac{\mu_s^2}{2}s^2 + \frac{\lambda_s}{4}s^4.$$

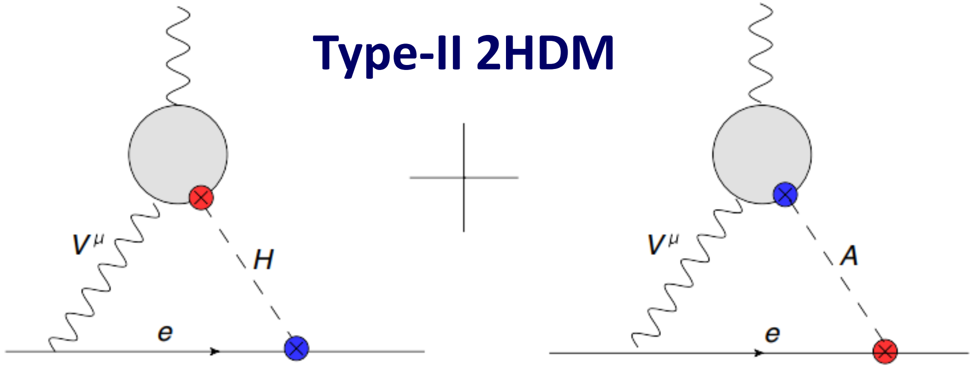
A dimension-5 operator is needed

$$-\frac{y_t}{\sqrt{2}}h\bar{t}_L\left(1+i\frac{s}{\Lambda}\right)t_R + \text{H.c.}$$

J. R. Espinosa, B. Gripaios, T. Konstandin and F. Riva, JCAP 1201, 012 (2012)
J. M. Cline and K. Kainulainen, JCAP 1301, 012 (2013)

(2) Cancellation mechanism for electron EDM contribution

Type-II 2HDM



L. Bian, T. Liu, J. Shu, Phys. Rev. Lett. 115 (2015)

Aligned 2HDM

S. Kanemura, M. Kubota, K. Yagyu, JHEP 08 (2020) 026

(3) There might be spontaneous CP violation only at the finite temperature. At T=0, the CP symmetry is restored.

A complex singlet scalar field extension of SM

$$\begin{aligned} V &= -\mu^2(H^\dagger H) + \lambda(H^\dagger H)^2 - \mu_A^2(S^\dagger S) + \lambda_1(S^\dagger S)^2 \\ &\quad +\lambda_2(H^\dagger H)(S^\dagger S) - \frac{1}{2}\mu_B^2 S^2 + \frac{1}{2}\lambda_3 S^4 + \text{h.c.} \end{aligned}$$

A dimension-5 operator is needed

$$\frac{S}{\Lambda}\bar{Q}_{3L}\tilde{H}t_R + \text{H.c.}$$

or a UV-completed model with a vector-like heavy quark.

W. Chao, Phys. Lett. B 796 (2019), 102-106.

A pseudoscalar field extension of 2HDM

$$V_{\rm 2HDM} = \mu_1^2\,|H_1|^2 + \mu_2^2\,|H_2|^2 - \left[\mu_{12}^2\,H_1^\dagger H_2 + {\rm h.c.}\right]$$
$$+ \frac{\lambda_1}{2}\,|H_1|^4 + \frac{\lambda_2}{2}\,|H_2|^4 + \lambda_3\,|H_1|^2\,|H_2|^2$$
$$+ \lambda_4\left|H_1^\dagger H_2\right|^2 + \frac{1}{2}\left[\lambda_5\left(H_1^\dagger H_2\right)^2 + {\rm h.c.}\right] ,$$
$$V_a = \frac{\mu_a^2}{2}\,a^2 + \frac{\lambda_a}{4}a^4 + \left(i\,\kappa\,a\,H_1^\dagger H_2 + {\rm h.c.}\right)$$
$$+ \lambda_{aH_1}\,a^2\,|H_1|^2 + \lambda_{aH_2}\,a^2\,|H_2|^2 \ .$$

S. J. Huber, K. Mimasu and J. M. No, Phys.Rev.D 107 (2023) , 075042

Some other discussions on electron EDM and CP violation:

J. Liu, Y. Nakai, Y. Shigekami, M. Song, Probing CP violation in dark sector through the electron electric dipole moment, JHEP 02 (2024) 082;
Y. Li, M. J. Ramsey-Musolf, J.-H. Yu, Does the Electron EDM Preclude Electroweak Baryogenesis?, arXiv:2404.19197;
X. Yang, M.-H. Guo, J.-L. Yang, Q.-H. Li, T.-F. Feng, Electroweak baryogenesis and electron EDM in the TNMSSM, arXiv: 2502.11409
……..

2HDM with a complex singlet scalar (2HDMS)

The scalar potential is given as

$$\begin{aligned} V =& m_{11}^2(\Phi_1^\dagger\Phi_1) + m_{22}^2(\Phi_2^\dagger\Phi_2) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) \\ &+\lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \left[\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \lambda_6(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) + \lambda_7(\Phi_2^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + \text{h.c.}\right] \\ &+m_S^2 SS^* + \left[\frac{m_S'^2}{2}SS + \text{h.c.}\right] + \left[\frac{\lambda_1''}{24}S^4 + \text{h.c.}\right] + \left[\frac{\lambda_2''}{6}S^2SS^* + \text{h.c.}\right] \\ &+SS^*\left[\lambda_1'\Phi_1^\dagger\Phi_1 + \lambda_2'\Phi_2^\dagger\Phi_2\right] + \frac{\lambda_3''}{4}(SS^*)^2 + \left[S^2(\lambda_4'\Phi_1^\dagger\Phi_1 + \lambda_5'\Phi_2^\dagger\Phi_2) + \text{h.c.}\right] \\ &+\left[\lambda_6' SS^*\Phi_2^\dagger\Phi_1 + \lambda_7'(SS + S^*S^*)\Phi_2^\dagger\Phi_1 + \text{h.c.}\right] \\ &+\left[-m_{12}^2\Phi_2^\dagger\Phi_1 + \boxed{\frac{\mu}{2}(S - S^*)\Phi_1^\dagger\Phi_2} + \text{h.c.}\right], \end{aligned}$$

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{(v_1+\rho_1+i\eta_1)}{\sqrt{2}} \end{pmatrix}, \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{(v_2+\rho_2+i\eta_2)}{\sqrt{2}} \end{pmatrix}, S = \frac{(\chi + i\eta_s)}{\sqrt{2}},$$

$$v = \sqrt{v_1^2 + v_2^2} = 246 \text{ GeV}$$

$$\tan\beta \equiv v_2 / v_1$$

A discrete symmetry is imposed $S \to -S^*$

In the real parametrization: $\chi \to -\chi\ , \eta_s \to \eta_s$

χ **may be as a candidate of DM.**

The potential minimization conditions

$$m_{11}^2 = m_{12}^2 t_\beta - \frac{1}{2} v^2 \left(\lambda_1 c_\beta^2 + \lambda_{345} s_\beta^2\right) ,$$

$$m_{22}^2 = m_{12}^2 / t_\beta - \frac{1}{2} v^2 \left(\lambda_2 s_\beta^2 + \lambda_{345} c_\beta^2\right) ,$$

In addition to the 125 GeV Higgs boson *h*, the physical scalar spectrum contains a CP-even state *H*, a DM candidate χ, two neutral pseudoscalars *A* and *X*, and a pair of charged scalar $H^\pm$.

The parameters in the scalar potential is expressed as

$$v^2\lambda_1 = \frac{m_H^2 c_\alpha^2 + m_h^2 s_\alpha^2 - m_{12}^2 t_\beta}{c_\beta^2}, \quad v^2\lambda_2 = \frac{m_H^2 s_\alpha^2 + m_h^2 c_\alpha^2 - m_{12}^2 t_\beta^{-1}}{s_\beta^2},$$

$$v^2\lambda_3 = \frac{(m_H^2 - m_h^2) s_\alpha c_\alpha + 2 m_{H^\pm}^2 s_\beta c_\beta - m_{12}^2}{s_\beta c_\beta}, \quad v^2\lambda_4 = \frac{(\hat{m}_A^2 - 2 m_{H^\pm}^2) s_\beta c_\beta + m_{12}^2}{s_\beta c_\beta},$$

$$v^2\lambda_5 = \frac{-\hat{m}_A^2 s_\beta c_\beta + m_{12}^2}{s_\beta c_\beta}, \text{ with } \hat{m}_A^2 = m_A^2 c_\theta^2 + m_X^2 s_\theta^2.$$

$$m_S^2 = \frac{1}{2}\left(m_\chi^2 + m_A^2 s_\theta^2 + m_X^2 c_\theta^2 - \lambda_1' v^2 c_\beta^2 - \lambda_2' v^2 s_\beta^2\right),$$

$$m_S'^2 = \frac{1}{2}\left(m_\chi^2 - m_A^2 s_\theta^2 - m_X^2 c_\theta^2 - 2\lambda_4' v^2 c_\beta^2 - 2\lambda_5' v^2 s_\beta^2\right),$$

$$\mu = \frac{\sqrt{2}(m_X^2 - m_A^2)}{v} s_\theta c_\theta,$$

The general Yukawa interactions are written as:

$$
\begin{aligned}
-\mathcal{L} \;=\; & Y_{u2}\,\overline{Q}_L\,\tilde{\Phi}_2\,u_R + Y_{d2}\,\overline{Q}_L\,\Phi_2\,d_R + Y_{\ell 2}\,\overline{L}_L\,\Phi_2\,e_R \\
& + Y_{u1}\,\overline{Q}_L\,\tilde{\Phi}_1\,u_R + Y_{d1}\,\overline{Q}_L\,\Phi_1\,d_R + Y_{\ell 1}\,\overline{L}_L\,\Phi_1\,e_R + \text{h.c.}\,,
\end{aligned}
$$

In order to avoid the tree-level favour changing neutral current, we take the Yukawa interactions to be aligned

A. Pich, P. Tuzon, Phys. Rev. D 80, (2009) 091702..

$$
\begin{aligned}
(Y_{u1})_{ii} &= \frac{\sqrt{2}m_{ui}}{v}(c_\beta - s_\beta\kappa_u), \qquad (Y_{u2})_{ii} = \frac{\sqrt{2}m_{ui}}{v}(s_\beta + c_\beta\kappa_u), \\
(Y_{\ell 1})_{ii} &= \frac{\sqrt{2}m_{\ell i}}{v}(c_\beta - s_\beta\kappa_\ell), \qquad (Y_{\ell 2})_{ii} = \frac{\sqrt{2}m_{\ell i}}{v}(s_\beta + c_\beta\kappa_\ell), \\
(X_{d1})_{ii} &= \frac{\sqrt{2}m_{di}}{v}(c_\beta - s_\beta\kappa_d), \qquad (X_{d2})_{ii} = \frac{\sqrt{2}m_{di}}{v}(s_\beta + c_\beta\kappa_d).
\end{aligned}
$$

The couplings of the neutral Higgs bosons with respect to the SM are given by

$$
\begin{aligned}
& y_V^h = \sin(\beta-\alpha),\;\; y_f^h = \left[\sin(\beta-\alpha) + \cos(\beta-\alpha)\kappa_f\right], \\
& y_V^H = \cos(\beta-\alpha),\;\; y_f^H = \left[\cos(\beta-\alpha) - \sin(\beta-\alpha)\kappa_f\right] \\
& y_V^A = 0,\;\; y_A^f = -i\kappa_f\;(\text{for } u)c_\theta,\;\; y_f^A = i\kappa_f c_\theta\;(\text{for } d,\;\ell), \\
& y_V^X = 0,\;\; y_X^f = -i\kappa_f\;(\text{for } u)s_\theta,\;\; y_f^X = i\kappa_f s_\theta\;(\text{for } d,\;\ell).
\end{aligned}
$$

Theoretical and experimental constraints

We identify the lightest CP even Higgs boson *h* as the observed 125 GeV state, and take sin(β-α) = 1 in order to avoid the constraints of the 125 GeV Higgs signal data.

We assume κ_u, κ_d, κ_ℓ to be small enough so that Higges can satisfy the exclusion limits of searches for additional Higgs bosons at the collider and the constraints of flavor observables.

$$
\begin{aligned}
S &= \frac{1}{\pi m_Z^2}\left[c_\theta^2 F_S(m_Z^2, m_H^2, m_A^2) + s_\theta^2 F_S(m_Z^2, m_H^2, m_X^2) - F_S(m_Z^2, m_{H\pm}^2, m_{H\pm}^2)\right],\\
T &= \frac{1}{16\pi m_W^2 s_W^2}\left[-c_\theta^2 F_T(m_H^2, m_A^2) - s_\theta^2 F_T(m_H^2, m_X^2) + F_T(m_{H\pm}^2, m_H^2)\right.\\
&\quad \left. + c_\theta^2 F_T(m_{H\pm}^2, m_A^2) + s_\theta^2 F_T(m_{H\pm}^2, m_X^2)\right],\\
U &= \frac{1}{\pi m_W^2}\left[F_S(m_W^2, m_{H\pm}^2, m_H^2) - 2F_S(m_W^2, m_{H\pm}^2, m_{H\pm}^2)\right.\\
&\quad \left. + c_\theta^2 F_S(m_W^2, m_{H\pm}^2, m_A^2) + s_\theta^2 F_S(m_W^2, m_{H\pm}^2, m_X^2)\right]\\
&\quad - \frac{1}{\pi m_Z^2}\left[c_\theta^2 F_S(m_Z^2, m_H^2, m_A^2) + s_\theta^2 F_S(m_Z^2, m_H^2, m_X^2)\right.\\
&\quad \left. - F_S(m_Z^2, m_{H\pm}^2, m_{H\pm}^2)\right],
\end{aligned}
$$

In addition to the vacuum stability, perturbativity, and tree-level unitarity, we consider the constraints of S, T, U parameters

H.-J. He, N. Polonsky, S. Su, Phys.Rev. D 64, (2001) 053004;
H. E. Haber, D. Oneil, Phys. Rev. D83, (2011) 055017

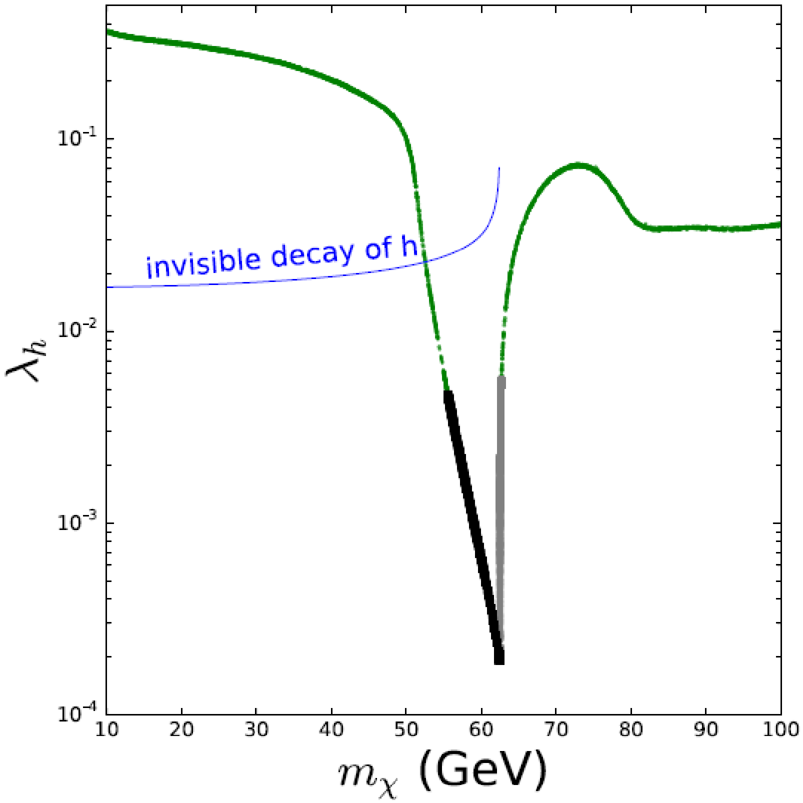
Dark matter

The two neutral CP-even Higgs (h, H) can mediate the interactions of DM,

$$\lambda_h \equiv (\lambda_2' + 2\lambda_5')v s_\beta c_\alpha - (\lambda_1' + 2\lambda_4')v c_\beta s_\alpha,$$

$$\lambda_H \equiv (\lambda_2' + 2\lambda_5')v s_\beta s_\alpha + (\lambda_1' + 2\lambda_4')v c_\beta c_\alpha.$$

We take λ_H=0, and study a light DM whose freeze-out temperature is much lower than that of EWPT.



A 95 GeV Higgs boson in the 2HDMS

The CMS and ATLAS reported a 3.1σ diphoton excess around 95.4 GeV

$$\mu_{\gamma\gamma}^{exp} = \mu_{\gamma\gamma}^{ATLAS+CMS} = 0.24^{+0.09}_{-0.08},$$

There is a 2.3σ excess in the e+e− → Z(ϕ → $b\bar{b}$) searches at LEP in the same mass region,

$$\mu_{b\bar{b}}^{exp} = 0.117 \pm 0.057$$

CMS collaboration, JHEP 05 (2024), 316; ATLAS Collaboration, JHEP 01 (2025), 053; T. Biekotter, S. Heinemeyer and G. Weiglein, Phys. Rev. D 109 (2024), 035005; ALEPH, DELPHI, L3 and OPAL, Phys. Lett. B 565 (2003), 61-75.

At zero temperature, χ has a nonzero VEV and mixes with the two CP-even scalar in the Higgs doublet fields. The lightest mixed state can serve as the 95GeV Higgs boson.

$$(h_1, h_2, h_3) = (\rho_1, \rho_2, \chi) R^T,$$

$$R = \begin{pmatrix} -c_1 c_2 & s_1 c_2 & s_2 \\ s_1 c_3 - c_1 s_2 s_3 & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\ s_1 s_3 - c_1 s_2 c_3 & -s_1 s_2 c_3 - c_1 s_3 & c_2 c_3 \end{pmatrix},$$

We assume the Yukawa coupling matrices to be aligned, and obtain the couplings of the neutral Higgs bosons with respect to the SM,

$$y_V^{h_1} = c_2 c_{\beta 1},\ y_f^{h_1} = c_2 \left(c_{\beta 1} - s_{\beta 1}\kappa_f\right),$$

$$y_V^{h_2} \simeq |s_2| s_{\beta 13} + \frac{c_2^2}{2} c_3 s_{\beta 1},\ y_f^{h_2} \simeq |s_2| \left(s_{\beta 13} + c_{\beta 13}\kappa_f\right) + \frac{c_2^2}{2} c_3 \left(s_{\beta 1} + c_{\beta 1}\kappa_f\right),$$

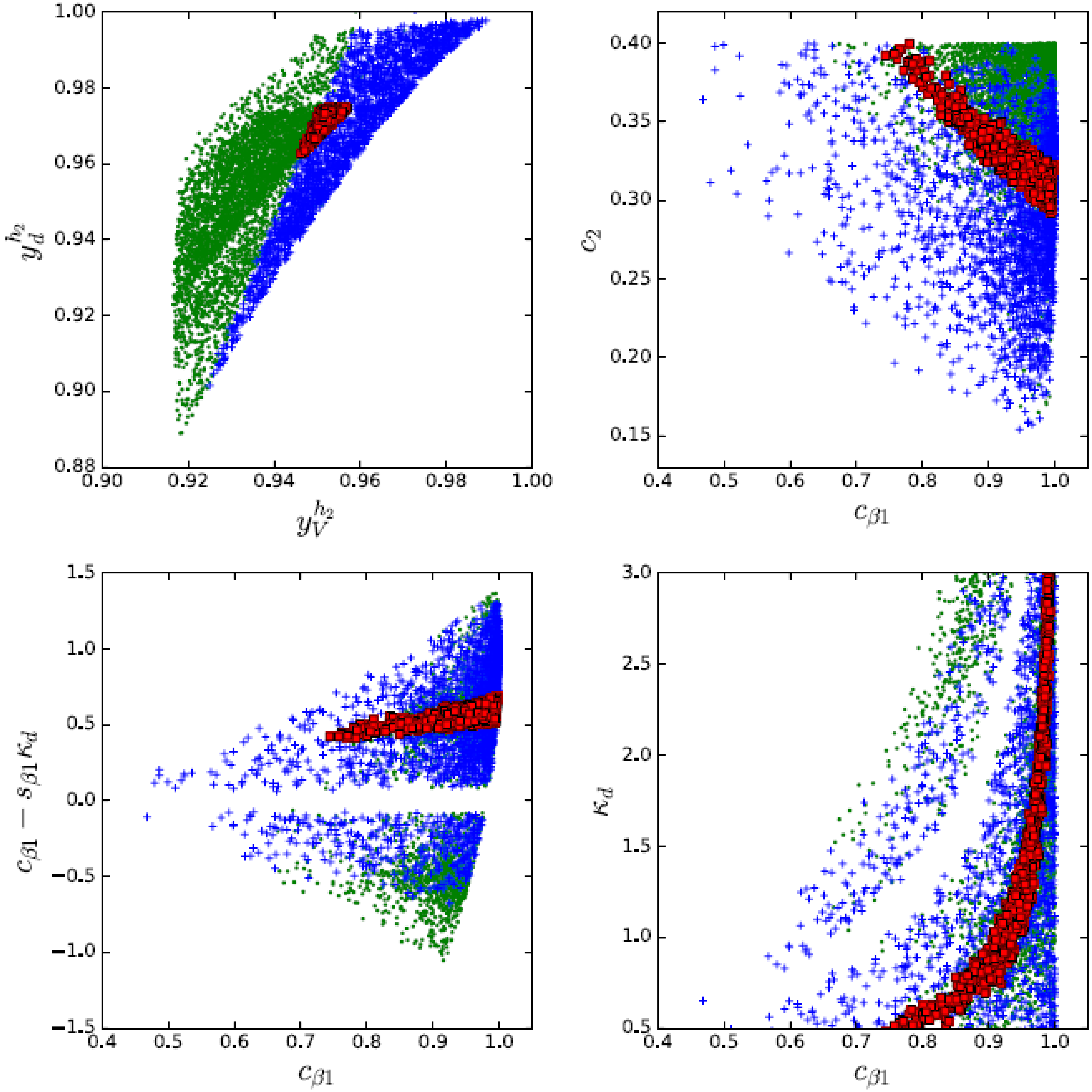
$$y_V^{h_3} \simeq |s_2| c_{\beta 13} - \frac{c_2^2}{2} c_3 s_{\beta 1},\ y_f^{h_3} \simeq |s_2| \left(c_{\beta 13} - s_{\beta 13}\kappa_f\right) - \frac{c_2^2}{2} c_3 \left(s_{\beta 1} + c_{\beta 1}\kappa_f\right),$$

$$y_V^A = 0,\ y_A^f = -i\kappa_f\ (\text{for } u) c_4,\ y_f^A = i\kappa_f c_4\ (\text{for } d,\ \ell),$$

$$y_V^X = 0,\ y_X^f = i\kappa_f\ (\text{for } u) s_4,\ y_f^X = -i\kappa_f s_4\ (\text{for } d,\ \ell),$$

$$c_\beta \equiv \cos(\beta - \alpha_1), s_\beta \equiv \sin(\beta - \alpha_1),\quad s_{\beta 13} \equiv \sin(\beta - \alpha_1 - \text{sgn}(s_2)\alpha_3) \quad c_{\beta 13} \equiv \cos(\beta - \alpha_1 - \text{sgn}(s_2)\alpha_3)$$

We take h_1 as the 95 GeV Higgs boson and h_2 as the 125 GeV Higgs boson.



$y_d^{h_2}$
$y_V^{h_2}$
c_2
$c_{\beta 1}$
$c_{\beta 1} - s_{\beta 1}\kappa_d$
$c_{\beta 1}$
κ_d
$c_{\beta 1}$

Electroweak phase transition and EWBG

To analyze the electroweak PT, one needs the effective potential of the model at the finite temperature. The neutral components of Φ_1 and Φ_2 are parametrized as $\frac{h_1}{\sqrt{2}}$ and $\frac{h_2+ih_3}{\sqrt{2}}$.

Here we take a gauge invariant approximation, which keeps only the thermal mass terms in the high-temperature expansion in addition to the tree level potential,

$$V_{eff}(h_1,h_2,h_3,\chi,\eta_s) = \frac{1}{2}(m_{11}^2+\Pi_{h_1})h_1^2 + \frac{1}{2}(m_{22}^2+\Pi_{h_2})(h_2^2+h_3^2) + \frac{1}{2}(m_S^2+{m'_S}^2+\Pi_\chi)\chi^2$$
$$+\frac{1}{2}(m_S^2-{m'_S}^2+\Pi_{\eta_s})\eta_s^2 + \frac{1}{8}(\lambda_1 h_1^4+\lambda_2 h_2^4+\lambda_2 h_3^4) + \frac{1}{4}\lambda_{345}h_1^2h_2^2 + \frac{1}{4}\bar{\lambda}_{345}h_1^2h_3^2$$
$$+\frac{\lambda_2}{4}h_3^2h_2^2 - m_{12}^2h_1h_2 - \frac{\mu}{\sqrt{2}}h_3\eta_sh_1 + \frac{\lambda'_1}{4}(\chi^2+\eta_s^2)h_1^2 + \frac{\lambda'_2}{4}(\chi^2+\eta_s^2)(h_2^2+h_3^2)$$
$$+\frac{\lambda'_4}{2}(\chi^2-\eta_s^2)h_1^2 + \frac{\lambda'_5}{2}(\chi^2-\eta_s^2)(h_3^2+h_2^2) + (\frac{\lambda''_1}{48}+\frac{\lambda''_3}{16})(\chi^4+\eta_s^4) + \frac{1}{8}(\lambda''_3-\lambda''_1)\chi^2\eta_s^2,$$

$$\Pi_{\varphi_1} = \left[\frac{9g^2}{2}+\frac{3g'^2}{2}+6\lambda_1+4\lambda_3+2\lambda_4+2\lambda'_1+6y_t^2(c_\beta-s_\beta\kappa_u)^2+6y_b^2(c_\beta-s_\beta\kappa_d)^2\right]\frac{T^2}{24},$$

$$\Pi_{\varphi_2} = \left[\frac{9g^2}{2}+\frac{3g'^2}{2}+6\lambda_2+4\lambda_3+2\lambda_4+2\lambda'_2+6y_t^2(s_\beta+c_\beta\kappa_u)^2+6y_b^2(s_\beta+c_\beta\kappa_d)^2\right]\frac{T^2}{24},$$

$$\Pi_{\varphi_3} = \Pi_{\varphi_2},$$

$$\Pi_\chi = [4\lambda'_1+4\lambda'_2+2\lambda''_2+2\lambda''_3+8\lambda'_4+8\lambda'_5]\frac{T^2}{24},$$

$$\Pi_{\eta_s} = [4\lambda'_1+4\lambda'_2-2\lambda''_2+2\lambda''_3-8\lambda'_4-8\lambda'_5]\frac{T^2}{24},$$

The configurations h_1, h_2, h_3 , χ, η_s are determined by differential equations

$$\frac{\mathrm{d}^2\phi_i}{\mathrm{d}r^2} + \frac{2}{r}\frac{\mathrm{d}\phi_i}{\mathrm{d}r} = \frac{\partial V_{eff}}{\partial \phi_i}, \quad (i = 1, 2, 3, 4, 5)$$

with the boundary conditions

$$\mathrm{d}\varphi_i/\mathrm{d}r|_{r=0} = 0 \text{ and } \varphi_i(r = \infty) = \varphi_{if}$$

The Euclidian action S_3 is determined by

$$S_3 = 4\pi \int_0^\infty \mathrm{d}r\, r^2 \left[\sum_{i=1}^{5} \frac{1}{2} \left(\frac{\mathrm{d}\phi_i}{\mathrm{d}r} \right)^2 + V_{eff} \right]$$

At the nucleation temperature T_n, one bubble is nucleated in one Hubble volume,

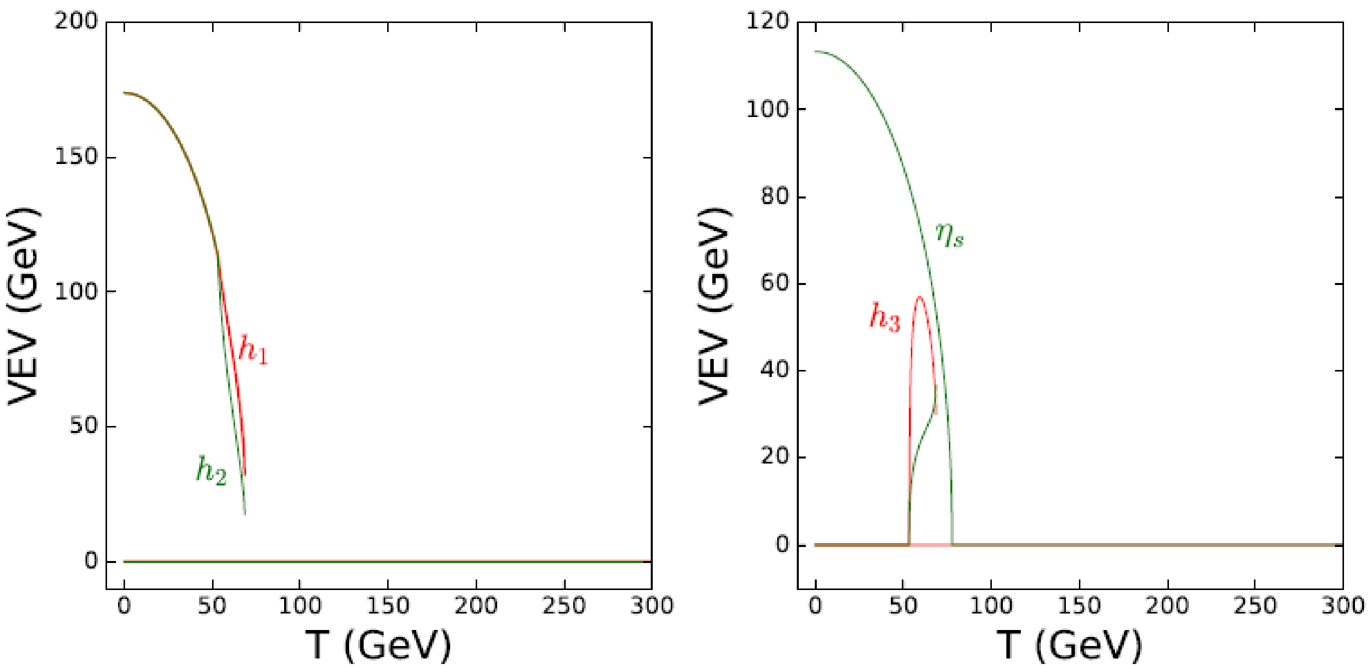
$$\int_{T_n}^{+\infty} \frac{\mathrm{d}T}{T} \frac{\Gamma(T)}{H(T)^4} = \mathcal{O}(1), \;\; \Gamma \;\approx\; A(T) e^{-S_3/T}$$

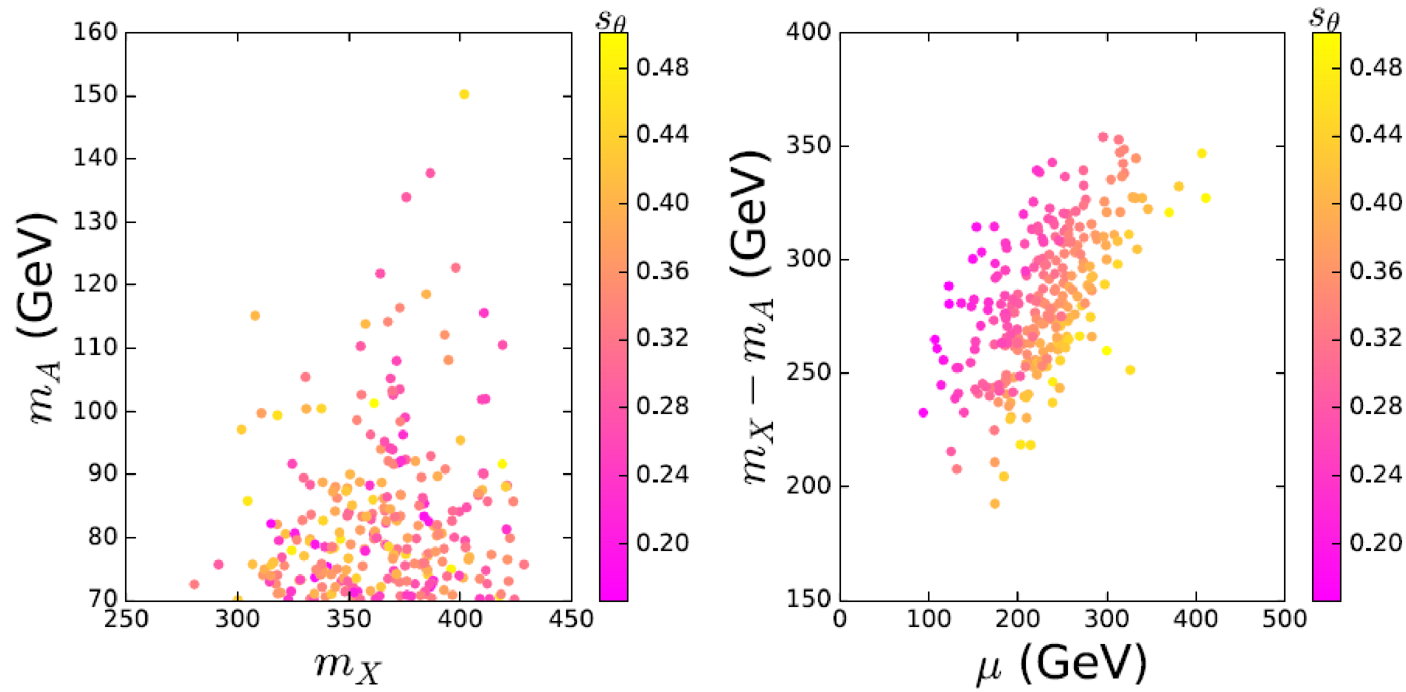
A. D. Linde, Phys. Lett. B 100, 37-40 (1981).

For the BP1, we assume that χ has no VEV at zero temperature and serves as a DM. The universe undergoes a three-step PT. The first step is a second-order PT. The second step is a strong first-order electroweak PT that breaks CP symmetry. The third step is a second-order PT leading to the observed vacuum at the current temperature and restoring CP symmetry.

m_h(GeV)	$m_H = m_{H^\pm}$(GeV)	m_χ(GeV)	m_A(GeV)	m_X(GeV)	m_{12}^2(GeV)^2
125.0	467.69	55.95	69.80	333.67	2740.09

t_β	$\sin(\beta-\alpha)$	$\sin\theta$	λ'_1	λ'_2	λ'_4	λ'_5	$\lambda''_1 = \lambda''_3$
1.0	1.0	0.324	2.293	1.351	-1.143	-0.675	1.839





m_A (GeV)
m_X
s_θ
160
150
140
130
120
110
100
90
80
70
250
300
350
400
450
0.48
0.44
0.40
0.36
0.32
0.28
0.24
0.20
$m_X - m_A$ (GeV)
μ (GeV)
s_θ
400
350
300
250
200
150
0
100
200
300
400
500
0.48
0.44
0.40
0.36
0.32
0.28
0.24
0.20

Transport equations and baryon asymmetry

Transport equations:

L. Fromme, S. J. Huber and M. Seniuch, JHEP11, 038 (2006).

$$
\begin{aligned}
0 =& 3v_W K_{1,t}\left(\partial_z \mu_{t,2}\right) + 3v_W K_{2,t}\left(\partial_z m_t^2\right)\mu_{t,2} + 3\left(\partial_z u_{t,2}\right) \\
&- 3\Gamma_y\left(\mu_{t,2} + \mu_{t^c,2} + \mu_{h,2}\right) - 6\Gamma_M\left(\mu_{t,2} + \mu_{t^c,2}\right) - 3\Gamma_W\left(\mu_{t,2} - \mu_{b,2}\right) \\
&- 3\Gamma_{ss}\left[\left(1 + 9K_{1,t}\right)\mu_{t,2} + \left(1 + 9K_{1,b}\right)\mu_{b,2} + \left(1 - 9K_{1,t}\right)\mu_{t^c,2}\right] , \\
0 =& 3v_W K_{1,t}\left(\partial_z \mu_{t^c,2}\right) + 3v_W K_{2,t}\left(\partial_z m_t^2\right)\mu_{t^c,2} + 3\left(\partial_z u_{t^c,2}\right) \\
&- 3\Gamma_y\left(\mu_{t,2} + \mu_{b,2} + 2\mu_{t^c,2} + 2\mu_{h,2}\right) - 6\Gamma_M\left(\mu_{t,2} + \mu_{t^c,2}\right) \\
&- 3\Gamma_{ss}\left[\left(1 + 9K_{1,t}\right)\mu_{t,2} + \left(1 + 9K_{1,b}\right)\mu_{b,2} + \left(1 - 9K_{1,t}\right)\mu_{t^c,2}\right] , \\
0 =& 3v_W K_{1,b}\left(\partial_z \mu_{b,2}\right) + 3\left(\partial_z u_{b,2}\right) - 3\Gamma_y\left(\mu_{b,2} + \mu_{t^c,2} + \mu_{h,2}\right) - 3\Gamma_W\left(\mu_{b,2} - \mu_{t,2}\right) , \\
&- 3\Gamma_{ss}\left[\left(1 + 9K_{1,t}\right)\mu_{t,2} + \left(1 + 9K_{1,b}\right)\mu_{b,2} + \left(1 - 9K_{1,t}\right)\mu_{t^c,2}\right] , \\
0 =& 4v_W K_{1,h}\left(\partial_z \mu_{h,2}\right) + 4\left(\partial_z u_{h,2}\right) - 3\Gamma_y\left(\mu_{t,2} + \mu_{b,2} + 2\mu_{t^c,2} + 2\mu_{h,2}\right) - 4\Gamma_h \mu_{h,2} , \\
S_t =& - 3K_{4,t}\left(\partial_z \mu_{t,2}\right) + 3v_W \tilde{K}_{5,t}\left(\partial_z u_{t,2}\right) + 3v_W \tilde{K}_{6,t}\left(\partial_z m_t^2\right) u_{t,2} + 3\Gamma_t^{\mathrm{tot}} u_{t,2} , \\
0 =& - 3K_{4,b}\left(\partial_z \mu_{b,2}\right) + 3v_W \tilde{K}_{5,b}\left(\partial_z u_{b,2}\right) + 3\Gamma_b^{\mathrm{tot}} u_{b,2} , \\
S_t =& - 3K_{4,t}\left(\partial_z \mu_{t^c,2}\right) + 3v_W \tilde{K}_{5,t}\left(\partial_z u_{t^c,2}\right) + 3v_W \tilde{K}_{6,t}\left(\partial_z m_t^2\right) u_{t^c,2} + 3\Gamma_t^{\mathrm{tot}} u_{t^c,2} , \\
0 =& - 4K_{4,h}\left(\partial_z \mu_{h,2}\right) + 4v_W \tilde{K}_{5,h}\left(\partial_z u_{h,2}\right) + 4\Gamma_h^{\mathrm{tot}} u_{h,2} ,
\end{aligned}
$$

The CP violation source term S_t is defined as

$$S_t = -v_W K_{8,t} \partial_z \left(m_t^2 \partial_z \theta_t \right) + v_W K_{9,t} \left(\partial_z \theta_t \right) m_t^2 \left(\partial_z m_t^2 \right)$$

$$m_t(z) = \frac{y_t}{\sqrt{2}} e^{i\varphi_Z(z)} (c_\beta h_1(z) + s_\beta \sqrt{h_2^2(z) + h_3^2(z)} e^{i\varphi_2(z)}),$$

$$= \frac{y_t}{\sqrt{2}} \sqrt{(c_\beta h_1(z) + s_\beta h_2(z))^2 + s_\beta^2 h_3^2(z)}\ e^{i\theta_t},$$

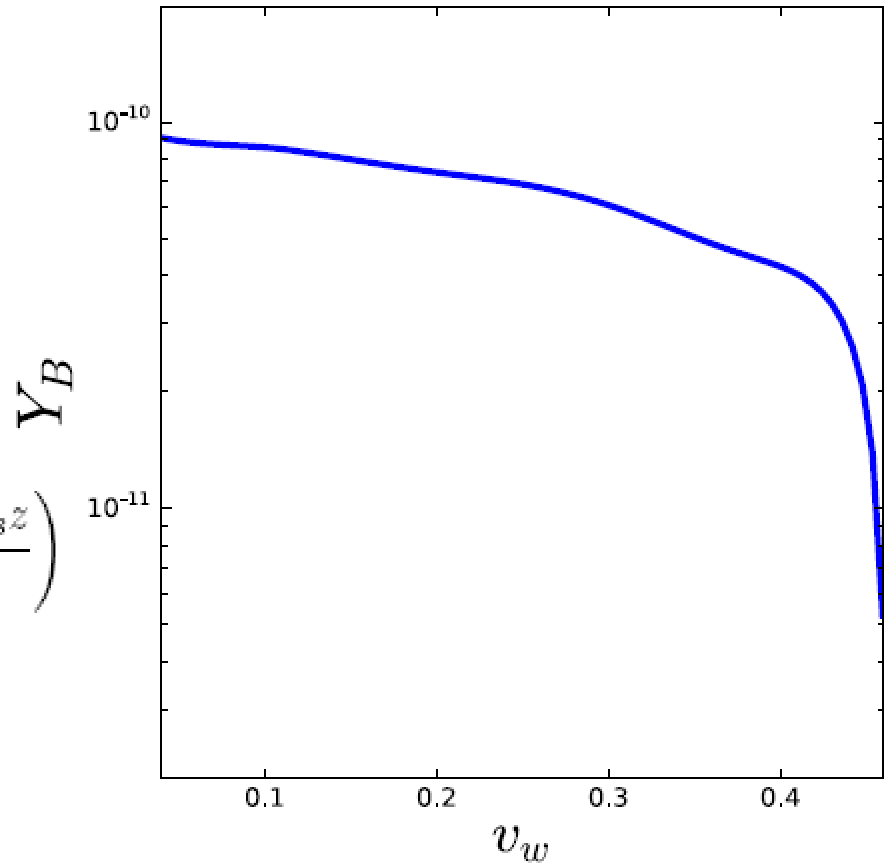
$$\varphi_2(z) = \arctan \frac{h_3(z)}{h_2(z)}, \quad \theta_t = \varphi_Z(z) + \arctan \frac{s_\beta h_3(z)}{c_\beta h_1(z) + s_\beta h_2(z)},$$

$$\partial_z \varphi_Z(z) = -\frac{h_2^2(z) + h_3^2(z)}{h_1^2(z) + h_2^2(z) + h_3^2(z)} \partial_z \varphi_2(z).$$

J. M. Cline, K. Kainulainen and M. Trott, JHEP 11, 089 (2011).

Next, the weak sphalerons convert the left-handed quark number into a baryon asymmetry, which can be calculated,

$$Y_B = \frac{405 \Gamma_{ws}}{4\pi^2 v_w g_* T_n} \int_0^\infty dz \mu_{B_L}(z) f_{sph}(z) \exp\left(-\frac{45 \Gamma_{ws} z}{4 v_w} \right)$$



Noticed that the effective potential have a Z_2 symmetry under which

$$h_3 \to -h_3 \quad \eta_s \to -\eta_s$$

There are two kinds of bubbles relating to θ_t and - θ_t, which produce baryon asymmetry of opposite signs. A soft Z_2 symmetry breaking term, $-i\mu_3(S - S^*)^3$ can be introduced to solve the problem.

For the BP1, the temperature of the Z_2-breaking PT is significantly higher than T_n of the electroweak PT, and the regions with - < η_s > can vanish when the electroweak PT takes place. The needed condition is

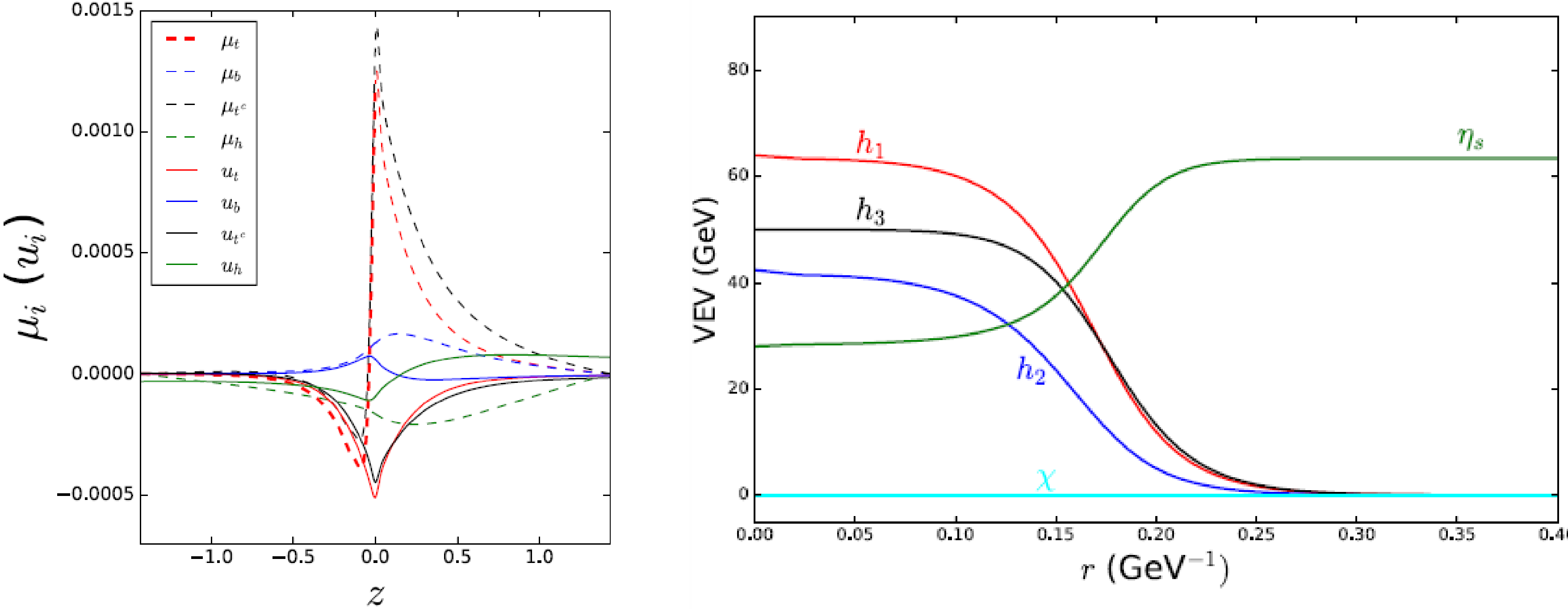
$$\Delta V/T^4 > 10^{-16} \Longrightarrow \mu_3 \sim 10^{-14}\text{GeV}$$

J. McDonald, Phys. Lett. B 323, 339 (1994);
J. R. Espinosa, B. Gripaios, T. Konstandin, and F. Riva, JCAP 01, 012 (2012).

Conclusions：

2HDMS is frequently utilized to explain dark matter and has recently been proposed to account for the observed diphoton and $b\bar{b}$ excesses around 95 GeV. We demonstrate that the model can simultaneously realize a finite-temperature spontaneous CP-violating electroweak phase transition, thereby providing a viable explanation for the baryon asymmetry via the electroweak baryogenesis mechanism.

Thanks！


μ_i (u_i)
0.0015
0.0010
0.0005
0.0000
−0.0005
−1.0
−0.5
0.0
0.5
1.0
z
μ_t
μ_b
μ_{t^c}
μ_h
u_t
u_b
u_{t^c}
u_h
VEV (GeV)
80
60
40
20
0
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
r (GeV^{-1})
h_1
h_3
h_2
η_s
χ